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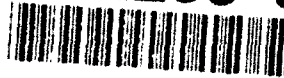
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HUMAN AUDITORY LOCALIZATION PERFORMANCE IN AZIMUTH

Mark A. Ericson
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CREW SYSTEMS DIRECTORATE
BIODYNAMICS AND BIOCOMMUNICATIONS DIVISION

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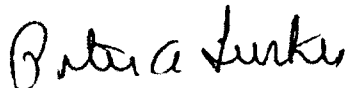thereto.

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FOR THE COMMANDER

PETER A. LURKER, Lt Col, USAF BSC
Acting Chief
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The Harry G. Armstrong Aerospace Medical Research Laboratory developed a unique research auditory localization facility for special, in-depth investigations of human auditory localization phenomena. A study was conducted in the facility to measure localization performance with three types of acoustic signals in azimuth; (1) natural, free-field acoustic cues heard with the ears uncovered, (2) simulated cues recorded at the ears of an acoustic manikin and presented over headphones, and (3) acoustic cues generated by an electronic auditory localization cue synthesizer and presented over headphones. Purposes of the study were (1) to evaluate relative localization accuracy and response time with the free-field, simulated and synthesized cues, (2) to examine the feasibility of localization of synthesized cues over headphones, and (3) to establish a data base of human auditory localization performance with these signals. Results across the three conditions averaged about 5 to 6 degrees in accuracy (magnitude error) and 3.5 to 4.5 seconds in response time. Localization performance with simulated and synthesized cues was essentially equivalent to natural (free-field) cues, demonstrating the capability of the localization cue synthesizer to present realistic directional sounds in azimuth.

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INTRODUCTION

Until recently, the scientific community was unable to electronically produce auditory localization (recognition of a sound's location) cues over headphones. Sounds presented over headphones were perceived to be at either ear or somewhere inside the listener's head. In 1930, Firestone (6) demonstrated an electro-acoustic method called the binaural process (also called simulated auditory localization), in which a dummy head was equipped with a microphone at the entrance to each ear canal. The acoustic signals present at each ear were transmitted over headphones (dichotic presentation) to a remote listener. The dummy's and the listener's heads were in fixed positions and the localization cues were presented over headphones. The binaural process was one of the first demonstrations of presenting directional information (not lateralized) over headphones and it remains in use today as an effective procedure for auditory localization research.

The Biological Acoustics Branch (AAMRL/BBA) constructed a research facility, similar to the one employed by Doll (5), and implemented an investigative effort to analyze the simulated auditory localization cue phenomenon as a precursor to the possible development of an electronic auditory localization cue synthesizer. The concept of a localization cue synthesizer is to provide directional information over headphones by electronic means instead of using acoustic coding processes, as in simulated auditory localization. Such an auditory localization cue synthesizer could be small, flexible, portable, and possibly provide cues that could be more accurately localized than under natural conditions. A cue synthesizer with capabilities such as these would have widespread applications both within and outside the government.

This investigative effort began with a study of the relative accuracy with which humans could localize sounds under natural conditions, with directional information acoustically coded via a manikin, and with directional information electronically coded by a cue synthesizer. As part of this effort, an electronic localization cue synthesizer was designed, developed, and evaluated in the comparative study. In general, results of the study revealed that localization by humans was relatively the same in each of the three test conditions. Most important, it demonstrated that the basic localization cue synthesizer was at least equally as effective in providing the directional cues that occur in the natural and simulated environments.

These findings provided impetus to the study efforts and to the development of potential applications for an auditory localization cue synthesizer. One of high interest is the military cockpit where the synthesizer could be coupled to the aircraft's present sensor systems and provide additional information about the aircraft situation, as well as systems external to the aircraft. The realization of directional audio technology in the cockpit may reduce visual workload, enhance the presentation of flight and threat information, thus, improving the pilot's situational awareness (14,23).

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BACKGROUND

Phenomena of directional hearing have been studied for over 100 years. Until recently, most of the work has focused on the process and mechanism of auditory localization. The scientific literature on auditory localization research is extensive and varied.

Lateralization

The earliest studies (9,11,17,18,19,24,25) describe the manner in which humans lateralize sounds. Lateralization is the perceptual relationship between the lateral displacement of a sound along the interaural axis and the attributes of the ear input signal (2). The sounds are perceived to be located at different points along the axis connecting the two ears while the interaural amplitude difference (IAD) and interaural time delay (ITD) of the ear input signals are varied (sounds appear stationary for non-varying IADs and ITDs).

Interaural Amplitude Difference -- The IAD is the amount of dissimilarity in sound pressure level of a signal measured at the entrances to the ear canals. In some studies, sounds with various IADs were presented over headphones to induce the lateralization effect. At one extreme, the sound would appear to be at the entrance of the ear canal. Fifteen to twenty decibels difference between the sound pressure level at each ear was required for the sound to be perceived to be located at the extreme lateral displacement. The interaural amplitude difference was believed by many to be the most important, if not the only cue needed for lateralizing sounds. However, the ITD was discovered to also induce the lateralization effect.

Interaural Time Delay -- The interaural time delay is the elapsed time from the incidence of a wave front at the entrance of one ear canal until the same wave front reaches the other ear canal (2). Studies conducted by von Hornbostel and Wertheimer (31) and von Bekesy (30) supported this concept. In these studies, a sound was presented to a subject with equal amplitude at both ears but with different time delays. The sound appeared to be somewhere along the interaural axis inside the head for signals with less than 630 microseconds of time delay. Above 630 microseconds, the sound appeared to be laterally displaced near the entrance to the ear canal. From 0.8 to 1 ms, the rate of change in lateral displacement with respect to the change in the ITD significantly decreased. Above 1 ms of delay, no increase in displacement was observed.

There are two types of interaural time delays that induce the lateralization effect: phase delay and envelope time delay of amplitude modulated signals. The ear can detect phase delays (differences in the time of arrival of a particular aspect of an auditory signal) in the frequency range from 20 to 1600 Hz. The neurons located between the inner ear and the central nervous system limit the response of the hearing system to time delay information. Due to a 1-2 ms refractory period of these neurons, signals above 1.6 kHz do not provide any usable phase delay information for localization (13,15,26,27,31,32).

Envelope time delays occur when the signals at each ear are in phase but the amplitude modulation envelope is shifted in time between the two ears. Leaky, Sayers and Cherry (10), Boerger (3) and Sakai and Inoue (20) conducted experiments which showed that envelope time delays in the frequency range of 100 to 20,000 Hz can be processed by the ear. In order for humans to localize sounds over headphones, more information than the cues used to lateralize sounds must be provided to the listener.

Localization

Auditory localization differs from lateralization in that the sound is perceived to originate from a location outside the listener's head. The ITD and audio spectra at the ear canal entrances are two cues which enable humans to determine the direction of sounds in a free-field environment. These cues are caused by dispersion, diffraction, and reflection of the sound by the head, pinnae, and torso of the listener. The change in the spectrum of a sound source from free space relative to the spectrum of the same sound in the ear canal of the listener is called the free-field or head related transfer function (HRTF) (2).

Pinnae -- The pinnae cause the most prominent features of the HRTF and have been studied for the longest time. In 1864, Schelhammer (21) attempted to explain the sound gathering effect of the pinna. He modeled the sound paths as geometric rays in trying to predict the reflections of the various folds of the pinna. Petri (16) continued the hypothesis by assuming that the pinnae shadowed the sounds from behind the open side. This assumption proved to be false. Dispersion and diffraction processes occur with auditory stimuli that are not taken into account by the geometric ray model. Shaw and Teranshi (22) analyzed the processing of sound in the pinna in the frequency domain. They were able to identify several resonant frequencies caused by the pinna. The useful resonances ranged from 4 to 12 kHz. They also hypothesized that these peaks and notches aided the listener in localizing sounds.

The head and possibly the torso can also play a role in directional hearing. Diffraction of sound around the head has been shown to influence the free-field transfer function below 2 kHz (8). These cues also help distinguish front to back reversals in the median plane. The differences in the spectra at each eardrum and the interaural time delay contain most of the directional information used in auditory localization.

Head Motion -- In addition to HRTF and ITD cues, head motion provides the listener with additional information for localizing sounds. Head motion improves localization performance in two ways: the sound can be brought into the listener's region of highest directional acuity and more information can be gathered from the different cues at various relative sound source locations to the listener's head (28,29). Head motion becomes critical in the localization of narrow band signals. The interaural differences of a narrow band signal may be the same for several different locations. The only way to resolve the ambiguity

would be with head or source motion. In particular, front to back reversals are almost completely avoided with head motion (4,7,12).

Doll's (5) facility corrected for head motion cues with the binaural process. The subject's head position was monitored by an electro-magnetic measuring instrument, a Polhemus 3-Space system. The instrument's sensor was attached to the top of a headphone headband. As the subject moved his head, the sound source location around the manikin was automatically processed to make the sound source over the headphones appear at the same relative location inside the room in which the listener was located. The facility included a semi-anechoic room with a circle of loudspeakers at 10° spacing, a Knowles Electronics Manikin for Acoustic Research (KEMAR) at the center of the circle with microphones at the entrances to the ear canals, a remote listening station, and a Polhemus 3-Space head tracking system. "Phantom" signals were created between the loudspeakers by presenting the sound source in phase and at different levels over two adjacent loudspeakers. The listener perceived the two sound sources as one since the two signals had identical spectra and had a relatively small angular separation.

Localization performance (accuracy and response time) in azimuth was evaluated with this facility in free-field and simulator (binaural) conditions. The subjects used a pistol-shaped, hand-held pointer to indicate the perceived direction of the sound source. The listeners' heads were allowed to move freely, but their laps were restricted by a belt securing them to a chair. The test stimuli consisted of pure tones, narrow band noise, wide band noise, pulses, and human speech. The dependance of localization performance on frequency content, rise time, pulse duration and complex (speech) signals was also measured. Generally, sounds containing information above 2 kHz and below 1.5 kHz and were greater than 300 ms in duration were the easiest to localize. Mean values of 4.3 to 5.1 degrees accuracy and 3 to 4 seconds response time were reported for the various stimuli. The importance of head motion in discriminating ambiguities and reversals was also found. Although the mechanism of localization was not discovered, much was found on the role of ITD, HRTF and head motion cues in localization. These experiments demonstrated the feasibility of simulated auditory localization over headphones.

OBJECTIVE

The research objectives of this effort were to measure human auditory localization performance in a free-field environment, over headphones using simulated cues from the facility, and over headphones using synthesized cues. A human auditory localization performance data base would be established upon completion of the effort.

APPROACH

Head related transfer functions and interaural time delays were measured on the acoustic manikin for selected acoustic signals. The HRTF and ITD data (and data from Doll) were used to develop an auditory localization

cue synthesizer. The accuracy and response times of subjects localizing acoustic signals in the free-field, simulator, and synthesizer conditions were measured. Analyses of these data verified that accurate directional information can be provided by synthetic cues presented over headphones and demonstrated the practical feasibility of an auditory localization cue synthesizer.

FACILITIES AND EQUIPMENT

The following apparatus were used to measure auditory localization performance in azimuth: a 24 loudspeaker ring, sound generation equipment, KEMAR manikin, Polhemus 3-Space Tracker, auditory localization cue synthesizer and an HP9845 desktop computer as the system controller.

Anechoic Chamber

The anechoic chamber and the control room adjacent to the chamber contain all of the equipment used in the experiments. All six interior surfaces of the test room are covered with four feet deep sound absorbing wedges by which the reflected sound is attenuated 60 to 120 dB from the level of the incident sound from 50 to 10,000 Hz. The interior dimensions of the chamber are 20 feet by 20 feet by 20 feet and are large enough to house the 14 feet diameter loudspeaker ring.

Loudspeaker Ring

The loudspeaker ring contained twenty-four 4.5 inch diameter loudspeakers equally positioned around a circle at the ear level of a listener (15° intervals). The structure was made of 0.5 inch diameter aluminum rods to minimize weight and reflective surfaces. The loudspeaker wiring harnesses were connected to a common switching board in the control room.

Acoustic Test Signals

The equipment which generated the pink noise, octave bands of noise, and speech test signals was located in the control room. A General Radio 1382 random noise generator provided the pink noise stimulus. A Bruel & Kjaer 2112 octave band filter set was connected to the output of the noise generator to provide the octave band noise stimuli. Male and female speech from a prerecorded audio cassette tape were presented through the sound generation system to the subjects. The complete sound generation and switching diagram is shown in Figure 1.

Head Tracker

The subject's head angle (azimuth) was monitored with a Polhemus 3-Space, electro-magnetic tracking system within +/- 0.5 degree of accuracy. The system consists of the electronics unit, the transmitter and the sensor. The transmitter was mounted approximately 18 inches above the subject's head. In the free-field condition, the sensor was attached to a Velcro strap that was wrapped snugly around the listener's

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head. In the simulation and synthesizer conditions, the sensor was secured on top of Sennheiser (HD-250) headphones.

KEMAR Manikin

A KEMAR manikin was used in the simulator condition to transduce the spatial auditory cues presented (in real-time) to the listener's headphones outside the chamber. KEMAR is an anthropomorphic chest-head (torso) manikin with interchangeable pinnae, and with acoustic couplers and microphones embedded at the eardrum locations. Zwislocki acoustic couplers and B&K 4165 half-inch microphones were used for these simulations. The 90th percentile pinnae were utilized on the manikin regardless of actual sizes of their individual pinnae.

Localization Cue Synthesizer

The spatial auditory cues were generated by the localization cue synthesizer for the synthesizer condition. The synthesizer is based on digital signal processing technology and it incorporates two Texas Instrument's TMS-320 processors. Basically, the cues were synthesized by encoding the acoustic test signals with the appropriate free-field head related transfer functions and interaural time delays measured on KEMAR. These synthesized signals were presented over binaural headphones.

System Controller

The HP 9845 computer was used as the system controller. The computer generated the sound source locations, presented the signals to the subjects, and recorded the subject's magnitude error and response time.

METHODOLOGY

Measurements were made of manikin HRTFs and ITDs and human auditory localization performance of free-field, simulated and synthesized cues. Performance response data were organized into the HRTF and ITD data bases. Measurements were made inside an anechoic chamber at one degree spacings in azimuth using the KEMAR anthropomorphic manikin with the 90th percentile pinnae. The one degree spacing is less than or equal to the minimum audible angle (14). Magnitude values of the transfer function were measured using a swept sine technique at logarithmic frequency spacings from 100 Hz to 20 kHz. The ITDs were measured consecutively with each HRTF measurement. A triangular pulse was generated and the time difference in the peaks of the signals at each ear was measured by a digital oscilloscope.

A localization synthesizer was designed based on three of the cues used by humans in auditory localization, ITD, HRTF, and, head motion. The HRTF and ITD cues were implemented on the synthesizer by digital filters for each of the 360 locations in azimuth. The listener's head motion was monitored by a Polhemus 3-Space tracker at a 54 Hz update rate. The head angle information was used to compute in real time the

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relative angle of the sound source over headphones for the simulated and the synthesized cue conditions. The synthesizer was developed primarily as a laboratory demonstration model for performance testing.

The human auditory localization facility was configured to present free-field, simulated and synthesized localization cues to a human subject and to record accuracy and response times. A horizontal ring of 24 loudspeakers equally spaced at 15 degree intervals presented the free-field stimuli. Either a single loudspeaker was used as a real source or two loudspeakers were phased together to create a "phantom" (33) source at any one degree location. The KEMAR manikin was placed in the center of the ring during the simulated cue sessions described earlier. The synthesizer presented the cues directly over headphones.

Human auditory localization performance data with the three types of acoustic signals were collected using the facility. Subjects from the general population responded to the presentation of the directional auditory stimuli by facing the perceived direction of the sound as quickly and as accurately as possible. The performance variables measured were the mean magnitude error, mean direction error, and mean response time. The data from the free-field, simulated, and synthesized stimulus conditions were treated by statistical analyses.

Experimental Design

The study employed a balanced measures, 2 X 3 X 6 X 10 mixed-factorial design with each test subject participating in all three conditions. The experimental design included four independent variables and three dependent variables. Three independent variables, conditions (3), stimuli (10), and sectors (6), were manipulated within-subjects. One random factor, subject, was nested within sex. The independent variables addressed in this study are listed in Table 1.

Independent Variables -- The three conditions were sounds presented (1) in an acoustic free-field, (2) over headphones via a manikin, and (3) over headphones via the synthesizer.

Ten different stimuli were used in the three conditions. The stimuli were defined as follows: wide band pink noise (100 Hz to 10 kHz); octave band pink noise centered at 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz; male speech (bandwidth = 3.5 kHz) and female speech (bandwidth = 6 kHz). Each stimulus was presented 72 times in three blocks of 24 trials for each condition.

Every set of 24 trials was pseudo-randomly generated such that four of the trials would be presented from each of the six sectors of the circle, as shown in Figure 3.

Subjects -- Ten subjects (five males and five females) were paid for their participation in the study. Each subject underwent an audiometric hearing test prior to participation in the study. To be eligible, the subject's hearing threshold levels could not be greater than 15 dB Sensation Level at any standard audiometric frequency (1).

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Each subject was administered an information form concerning the procedures prior to the experiment. All procedures and requirements of the Air Force pertaining to the subject's rights, protection, and safety were satisfied.

Dependent Variables — The dependent variables were (1) the mean magnitude error (MME), (2) the mean direction error (MDE) and (3) the mean response time (MRT). The means of the 72 trials were calculated at the end of each session. The mean magnitude error is defined as the absolute measure of the average difference in degrees between the actual direction of the stimulus and the subject's perceived direction of the stimulus. The mean direction error is defined as the arithmetic measure of the average difference (right + or left -) between the actual direction of the stimulus and the subject's perceived direction of the stimulus. The mean response time is defined as the time from stimulus onset until the subject's response indicating the perceived direction of the stimulus.

Table 1
Variables and Factor Levels for Study

Factor	Levels	Description
Condition	3	Free-field Simulator (Binaural) Synthesizer
Stimulus	10	Wide band pink noise Male Speech Female Speech Octave band noise centered at 125, 250, 500, 1K, 2K, 4K, 8K(Hz)
Sector	6	#1) 330-29° #2) 30-89° #3) 90-149° #4) 150-209° #5) 210-269° #6) 270-329°
Sex (Subject)	2	Male & female (5 of each)

PROCEDURES

Each subject participated in two practice sessions for each of the three test conditions (e.g., free-field, simulator, and synthesizer). Each practice session consisted of 72 trials using the wide band pink noise stimulus. The purpose of the practice session was to familiarize the subjects with the procedure, rather than to achieve a predetermined level of performance.

The acoustic stimuli were calibrated to 70 dB(A) sound pressure level (SPL) prior to the start of each session. The measurements were taken at the location of the subject's head in the center of the ring for the free-field condition. For the simulator and synthesizer conditions, the sound pressure level under each earcup of the headphones was set to 70 dB(A) as measured on a B&K 9cc acoustic coupler.

During a session of 24 trials, the subject was required to boresight the head tracker before each trial. This procedure was used to minimize the head tracker measurement errors that occur due to displacement of the subject's head from the center (reference) position. The stimuli were pulsed at two times per second (2 Hz) from the number one loudspeaker (azimuth = 0) so the subject could "boresight" the head tracker while looking at the loudspeaker and depressing the response button.

The subjects localized the target source with their eyes closed to eliminate any visual cues. Once the subject localized the sound source and faced the target source, the response switch was depressed a second time. The response data was displayed on the HP9845 for the experiment controller to validate before continuing. When the angle error was greater than 30 degrees or the response time was greater than 15 seconds elapsed time, the experimenter would pause the experiment and repeat the test point. When the error and time were acceptable the experimenter would allow the session to continue until all 24 trials were complete. The 24 trial process was repeated a total of three times per stimulus. Each session of 72 trials lasted 5 to 10 minutes. A subject completed two consecutive sessions before taking a half hour break.

Free-Field

In the control condition, auditory localization performance was measured in an acoustic free-field. The listener's ear canal was level with the horizontal loudspeaker ring. The experimenter assisted the subject in positioning the magnetic sensor on his/her head with Velcro straps. The door to the chamber was closed and the subject was prompted prior to the first stimulus. The subject checked that he/she was positioned in the center of the ring and prepared to boresight the head tracker. When the pulsed sound was presented, the subject faced the number one loudspeaker, pressed the response button, and turned to face the steady sound stimulus. The experimenter monitored the subject via a video camera to ensure proper execution of the task. An intercommunication system enabled audio communication between the subject and the experiment controller. Figure 1 shows the layout of the setup that was used for the free-field condition.

Simulator

In the simulator condition auditory localization performance over headphones was measured using the binaural process. The same paradigm, stimuli, and criteria measurements were used as in the free-field condition. The subject was located in the control room outside the anechoic chamber. KEMAR was positioned at the identical location of the listener's during the free-field measurements facing the 0 degree

position in the center of the ring. Figure 2 contains a layout of the set-up for the simulator condition.

Synthesizer

In the synthesizer condition auditory localization performance over headphones was measured using KEMAR's HRTF and ITD cues via the synthesizer. Unlike the other conditions, the cues were generated synthetically without the anechoic chamber facility. The audio stimuli were input to the synthesizer and output over the same headphones at the same location as in the simulator condition. Figure 4 contains a layout of the setup that was used for the synthesizer condition.

RESULTS

Four-factor analyses of variance (ANOVA) were performed on the data for the dependent variables mean magnitude error, mean directional error, and mean response time. Condition, stimulus, and sector were treated as within-subject variables and subject as a random factor nested within sex. A total of 21,600 observations were analyzed. In those cases where the ANOVA revealed significant effects, the Tukey and Bonferroni multiple comparison tests were conducted. The following will describe in more detail the results obtained for each dependent measure.

Mean Magnitude Error

The mean magnitude error (MME) of the subjects averaged across the three conditions was 5.2 degrees (SD =2.5°). Individual subject means ranged from 1.2 to 20.8 degrees. The mean magnitude errors as a function of condition, stimulus and sector are shown in the Appendix.

The ANOVA indicated significant differences among the stimuli, $F(9,72)=3.44$, $p=.0014$. The Bonferroni and Tukey multiple comparison tests indicated that the MME was greater for the 4 kHz stimulus (mean=6.3°, p less than or equal to .05) than for the other stimuli (range= 4.7 to 5.4°).

Significant differences were found across sectors $F(5,40) = 4.62$, $p=.0020$. Mean comparisons within the sectors revealed no significant differences between the simulator and synthesizer conditions. MMEs for the free-field were larger than for the simulator condition in sectors 4 (150-209°; means: 5.7 & 4.9°, respectively, $p=.0185$) and 5 (210-269°; means: 5.7 & 4.9°, respectively, $p=.0393$) and larger than for the synthesizer in sectors 4 (150-209°; means: 6.3 & 4.6, respectively, $p=.0039$) and 6 (270-329°; means 6.4 & 4.8°, respectively, $p=.0234$). These differences were statistically significant.

A statistically significant interaction was found between condition and sector, $F(10,80)=3.26$, $p=.0014$. Mean comparisons within the conditions indicated small differences among the sectors for the simulator and the synthesizer conditions. However, in the free-field condition, the MME was smaller in sector 1 (330-29°, mean 4.3°) than in the other five sectors (range: 5.7 to 7.2°). No other interactions were statistically

significant. These results are shown in Table 2 and a plot of the MME versus sector for each condition is shown in Figure 5.

Table 2
Summary of Analysis of Variance for Mean Magnitude Error

Source of variance	dF	SSQ	F-value	P-value
COND	2,16	578.62	2.80	0.0908
STIMULI	9,72	350.28	3.44	0.0014*
SECTOR	5,40	172.89	4.62	0.0020*
SEX	1,8	7.39	0.04	0.8457
COND*STIMULI	18,144	272.90	1.39	0.1447
COND*SECTOR	10,80	380.04	3.26	0.0014*
COND*SEX	2,16	15.87	0.08	0.9265
STIMULI*SECTOR	45,360	82.02	1.01	0.4654
STIMULI*SEX	9,72	180.50	1.77	0.0884
SECTOR*SEX	5,40	84.58	2.26	0.0667
COND*STIMULI*SECTOR	90,720	189.00	1.04	0.3747
COND*STIMULI*SEX	18,144	140.64	0.72	0.7901
COND*SECTOR*SEX	10,80	39.79	0.34	0.9668
STIMULI*SECTOR*SEX	45,360	96.69	1.19	0.2011
COND*STIM*SECTOR*SEX	90,720	190.04	1.05	0.3614

* Significant (p less than .05)

Mean Directional Error

The mean directional error (MDE) across subjects for the three conditions was -0.4 degrees (SD=4.9°). Individual subject means ranged from -20.5 to 13.5 degrees. MDE as a function of condition, stimulus and sector is shown in the Appendix.

A significant difference was found among the three stimulus conditions, $F(2,16)=13.19$, p=.0004. The simulator condition had more negative MDEs (range: -1.9 to -5.9°) than both the free-field (range: -0.4 to 2.5°) and synthesizer (range: -0.6 to 2.2°) conditions. There were no statistically significant MDE differences between the free-field and synthesizer within any of the stimuli.

A significant interaction was found between condition and stimuli, $F(18,144)=2.27$, p=.0039. As with the MME, the MDE with the 4 kHz stimulus in the simulator condition (-5.9°) was much worse than the average MDE in the synthesizer condition (2.2°).

There was a statistically significant interaction between condition, stimuli, and sex, $F(18,144)=1.78$, p=.0335. Across all stimuli, males responded with more positive (to the right) MDEs than did females (means = .09 and -.81°, respectively). There were no other significant interactions. These results are shown in Table 3 and a plot of the MDE versus stimuli for each condition is shown in Figure 6.

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Table 3
Summary of Analysis of Variance for Mean Direction Error

Source of variance	dF	SSQ	F-value	P-value
COND	2,16	8160.98	13.19	0.0004*
STIMULI	9,72	295.08	0.81	0.6050
SECTOR	5,40	281.50	0.92	0.4758
SEX	1,8	365.67	0.56	0.4744
COND*STIMULI	18,144	1320.65	2.27	0.0039*
COND*SECTOR	10,80	765.60	1.26	0.2683
COND*SEX	2,16	279.48	0.45	0.6444
STIMULI*SECTOR	45,360	161.33	0.72	0.9089
STIMULI*SEX	9,72	140.14	0.39	0.9379
SECTOR*SEX	5,40	10.00	0.03	0.9994
COND*STIMULI*SECTOR	90,720	401.40	0.99	0.5008
COND*STIMULI*SEX	18,144	1031.94	1.78	0.0335*
COND*SECTOR*SEX	10,80	48.05	0.08	0.9999
STIMULI*SECTOR*SEX	45,360	197.06	0.88	0.6886
COND*STIMULI*SECT*SEX	90,720	374.81	0.93	0.6666

* Significant (p less than .05)

Mean Response Time

The mean response time (MRT) of the subjects across the three conditions was 4.1 seconds ($SD=1.6°$). The individual means ranged from 1.2 to 9.4 seconds. MRT as a function of condition, stimulus and sector is shown the Appendix.

A significant difference was found for the MRT main effect condition, $F(2,16)=5.46$, $p=0.0156$. The free-field condition had a lower MRT (mean=3.5 s) than the simulator (mean=4.4 s) and synthesizer conditions (mean=4.3 s). A significant difference was found between some sectors, $F(5,40)=69.52$, $p=.0001$. In sector 1 (330-29°), directly in front of the subject, the MRT was the smallest (3.4 s) of all sectors across all conditions. Sectors 2 (30-89°, 3.8 s) and 6 (270-329°, 3.9 s) and 3 (90-149°, 4.3 s) and 5 (210-269°, 4.4 s) had similar MRTs. The MRT was longest when the stimulus was presented behind the subject (Sector 4; 150-209°, 4.8 s).

Significant differences were also found for the interaction of condition and stimuli $F(18,144)=2.17$, $p=0.0062$ and the interaction of condition, stimuli, sector, and sex, $F(90,720)=1.48$, $p=0.41$. Within the conditions, there was little difference among the stimuli for the free-field and synthesizer conditions. However, within the simulator condition the MRTs at 4 and 8 kHz were often significantly higher, 5.2 and 5.1 seconds, respectively, than the other 8 stimuli, p less than 0.1. A plot of the MRT versus stimuli for each condition is shown on Figure 7. A significant difference between the simulator and synthesizer conditions was found for the 8 kHz stimulus, $p=.0372$. Table 4 shows these results.

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Table 4
Summary of Analysis of Variance for Mean Response Time

Source of variance	dF	SSQ	F-value	P-value
COND	2,16	303.10	5.46	0.0156*
STIMULI	9,72	58.81	2.94	0.0050*
SECTOR	5,40	366.01	69.52	0.0001*
SEX	1,8	11.09	0.03	0.8599
COND*STIMULI	18,144	89.06	2.17	0.0062*
COND*SECTOR	10,80	4.43	0.98	0.4680
COND*SEX	2,16	13.61	0.25	0.7854
STIMULI*SECTOR	45,360	6.85	0.89	0.6666
STIMULI*SEX	5,40	13.66	0.68	0.7222
SECTOR*SEX	5,40	6.71	1.28	0.2935
COND*STIMULI*SECTOR	90,720	11.47	0.81	0.8972
COND*STIMULI*SEX	18,144	22.84	0.56	0.9246
COND*SECTOR*SEX	10,80	3.34	0.74	0.6859
STIMULI*SECTOR*SEX	45,360	5.14	0.67	0.9486
COND*STIM*SECTOR*SEX	90,720	20.99	1.48	0.0041*

* Significant (p less than .05)

Summary of Results

Table 5 shows the mean performance measures for the three conditions. There were no significant differences (p=.0908) for the MMEs across the three conditions. Significant differences were found for stimuli (p=.0014), sector (p=.0020) and the two-way interaction of condition and sector (p=.0014). Within conditions, the free-field MME in sector 1 (4.3°) had significantly less MME (p less than or equal to .0201) than the other 5 sectors (range 5.7 to 7.2°).

Significant differences were found for the MDE measure for condition (p=.0004), condition and stimuli (p=.0039) and condition, stimuli and sex (p=.0335). The simulator MDE (mean -3.4°) was negative (left) and the free-field (mean 1.3°) and synthesizer MDE (mean 1.0°) were positive (right).

There were significant differences found for the MRT measure for condition (p=.0156), stimuli (p=.0050), sector (p=.0001), condition and stimuli (p=.0062), and the four way interaction of condition, stimuli,

Table 5
Summary of Means

Condition	MME	MDE	MRT
Free-field	6.03	1.31	3.51
Simulator	4.82	-3.36	4.42
Synthesizer	4.84	0.98	4.34
Average	5.23	-0.36	4.09

sector and sex (p=.0041). Significantly more time (p=.0156) was required to respond in the simulator (4.4 s) and synthesizer (4.3 s) conditions than in the free-field (3.5 s) condition. The mean response time data showed no significant difference (p=.3971) for sectors 2 (30-89°) and 6 (270-329°).

DISCUSSION

The mean magnitude error for the free-field condition was higher than in the simulator and synthesizer conditions across sectors, except for the front sector. Overall, performance in the headphone conditions was not expected to be better than the overall performance in the free-field condition, since the cues in the headphone conditions were generated with a manikin whose head and pinnae did not exactly match those of any subject. The different room environments may have affected the subject's performance as observed by higher free-field mean magnitude error. Subjects stood on a platform which rested on cable suspension flooring for the free-field condition and they stood on solid flooring for the headphone conditions. The difficulty of turning on the platform may have caused greater localization error, especially when the sound source was located to the side or the rear of the subject (sectors 2 through 6). Also, the subjects were observed to have more difficulty staying directly underneath the electromagnetic transmitter in the free-field condition than in the headphone conditions.

The mean magnitude error for the free-field condition was also higher than the MME for the simulator and synthesizer conditions across stimuli, except for the simulator 4 kHz stimulus. In the simulator condition, the 4 kHz stimulus was separated from the other 9 stimuli by 0.71° using a least significant difference (LSD) procedure for comparing stimuli. The 4 kHz stimulus was the most difficult to localize of all the stimuli (MME=6.33°) and the most difficult to localize within the simulator (6.94°) and synthesizer (5.87°) conditions. The 4 KHz octave band noise was difficult to localize because humans are unable to process ITD cues above 1.5 KHz and only a portion of the HRTF cues are present in the 4 KHz region (Shaw, 1972).

The mean directional error was calculated to determine whether the subjects perceived the direction of the sound to be to the right or left of the actual direction. Mean direction error in the simulator condition (-3.36°) was quite different than in the free-field (1.31°) and synthesizer conditions (0.98°). Assuming both left and right signals from KEMAR to the headphones were balanced properly in the calibration procedure; this difference may be due to the software algorithm for the simulator condition. A prediction routine was used to turn on the next loudspeaker in the direction the subject was turning. Additional cues were provided to the listener by the phasing of the loudspeakers in producing phantom sources and by the clicking of the mechanical relays. Perhaps one or a combination of these cues caused the subjects to favor the left (negative) side in the simulator condition.

The free-field MRT (3.51 s) was shorter than the simulator and

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synthesizer MRT's (4.42 s and 4.34 s, respectively). In the simulator and synthesizer conditions, the subjects were able to turn faster than the head tracker (@ 54 Hz) could monitor. The headphone presentation of the sound source was delayed with respect to what the listener expected it to be as the listener's head rotation rate exceeded 54 Hz. It is believed that the subjects slowed down their head movement to compensate for the lag. An adequately fast head tracker (greater than 200 Hz) may allow humans to localize and track sounds over headphones as quickly as sounds presented in free-field conditions.

In all conditions, the stimulus was perceived to be elevated above the horizontal plane in front of the listener (330-29°). The degree of perceived elevation varied among subjects. The reason for this phenomenon is not yet known. The perceived elevation may have been caused by the lack of a visual cue coupled to the auditory stimulus in all conditions. The lack of multipath signals may also have degraded the perception of the actual elevation of the auditory event. In addition to the possible causes in all three conditions, the differences between the listener's and KEMAR's HRTF and ITD may have caused distortions in the perception of sound source's actual elevation in the headphone conditions.
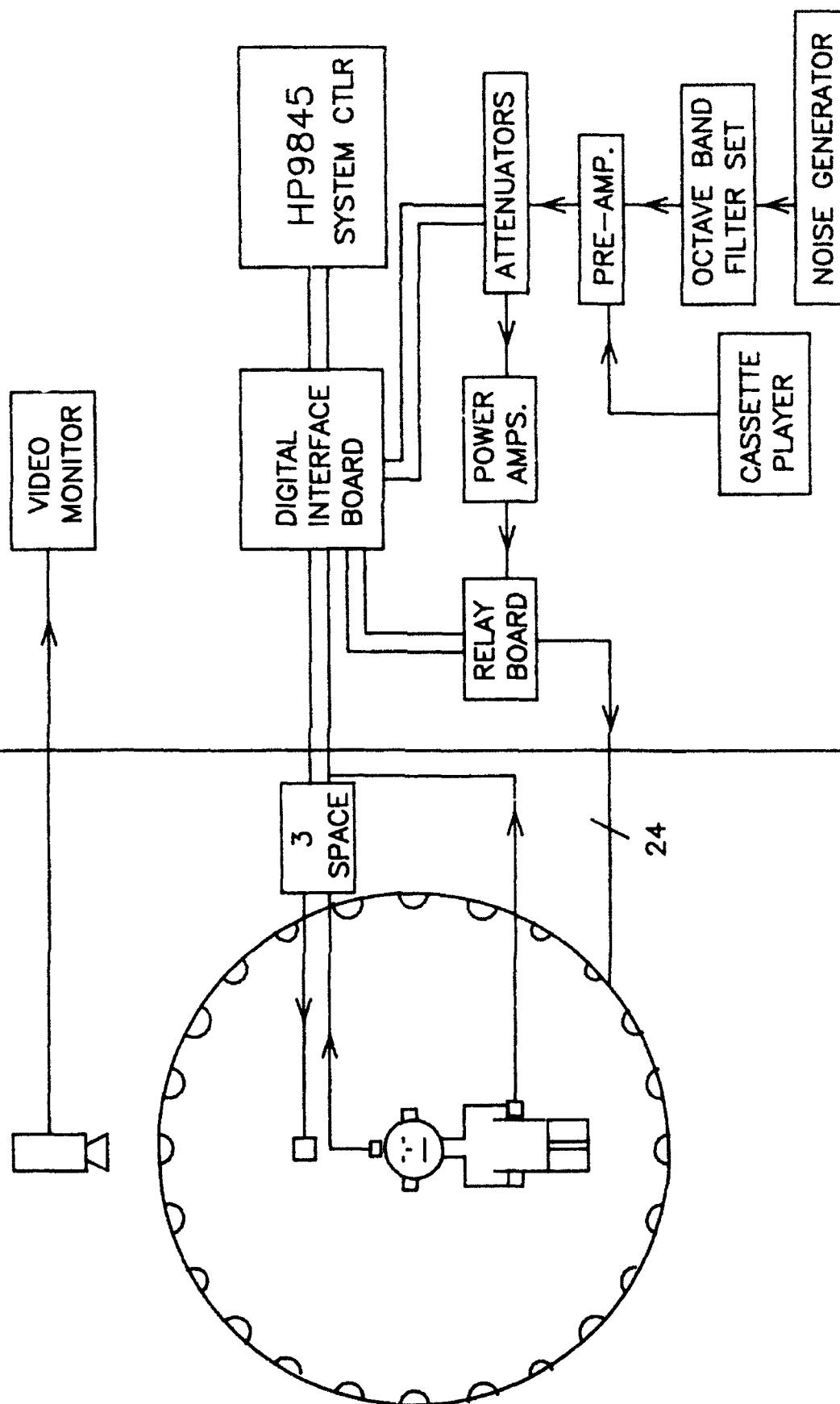
CONCLUSIONS/RECOMMENDATIONS

Human auditory localization performance in azimuth was quantified in the laboratory facility for free-field, simulated and synthesized cues. The average MME in the free-field (6.0°) was slightly higher than in the simulator (4.8°) and synthesizer (4.8°) conditions. Conversely, the average MRT in the free-field (3.5 s) was slightly less than in the simulator (4.4 s) and synthesizer (4.3 s) conditions. In the data analysis, several significant interactions were found across conditions, stimuli, and sectors as measured by magnitude error, directional error and response time. The analysis of the MME data showed that the 2 and 4 kHz stimuli were the most difficult to localize in the free-field condition, 6.6° and 6.2° error, respectively. The 4 kHz stimulus was the most difficult to localize in the simulator (6.9°) and synthesizer (5.9°) conditions. The MRT data analysis showed that sounds in front of the subject (330-29°) were localized with the least amount of time (3.4 s) and stimuli emanating behind the subject (150-209°) required the longest response time to localize (4.8 s).

The comparison of human auditory localization performance across the three conditions suggests the feasibility of using simulated and synthesized cues to provide directional information over headphones. Overall, localization accuracy in the headphone conditions slightly exceeded that in the free-field condition and response time in the free-field condition was slightly less than those in the headphone conditions. Although initial laboratory testing has demonstrated the feasibility of using synthesized cues, further research is necessary before localization cue synthesis can be used in a particular application.

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CONTROL ROOM

ANECHOIC CHAMBER

VIDEO MONITOR

HP9845 SYSTEM CTLR

DIGITAL INTERFACE BOARD

ATTENUATORS

PRE—AMP.

OCTAVE BAND FILTER SET

NOISE GENERATOR

POWER AMPS.

CASSETTE PLAYER

RELAY BOARD

3 SPACE

24

SETUP FOR FREE—FIELD HUMAN PERFORMANCE MEASUREMENTS

FIGURE 1
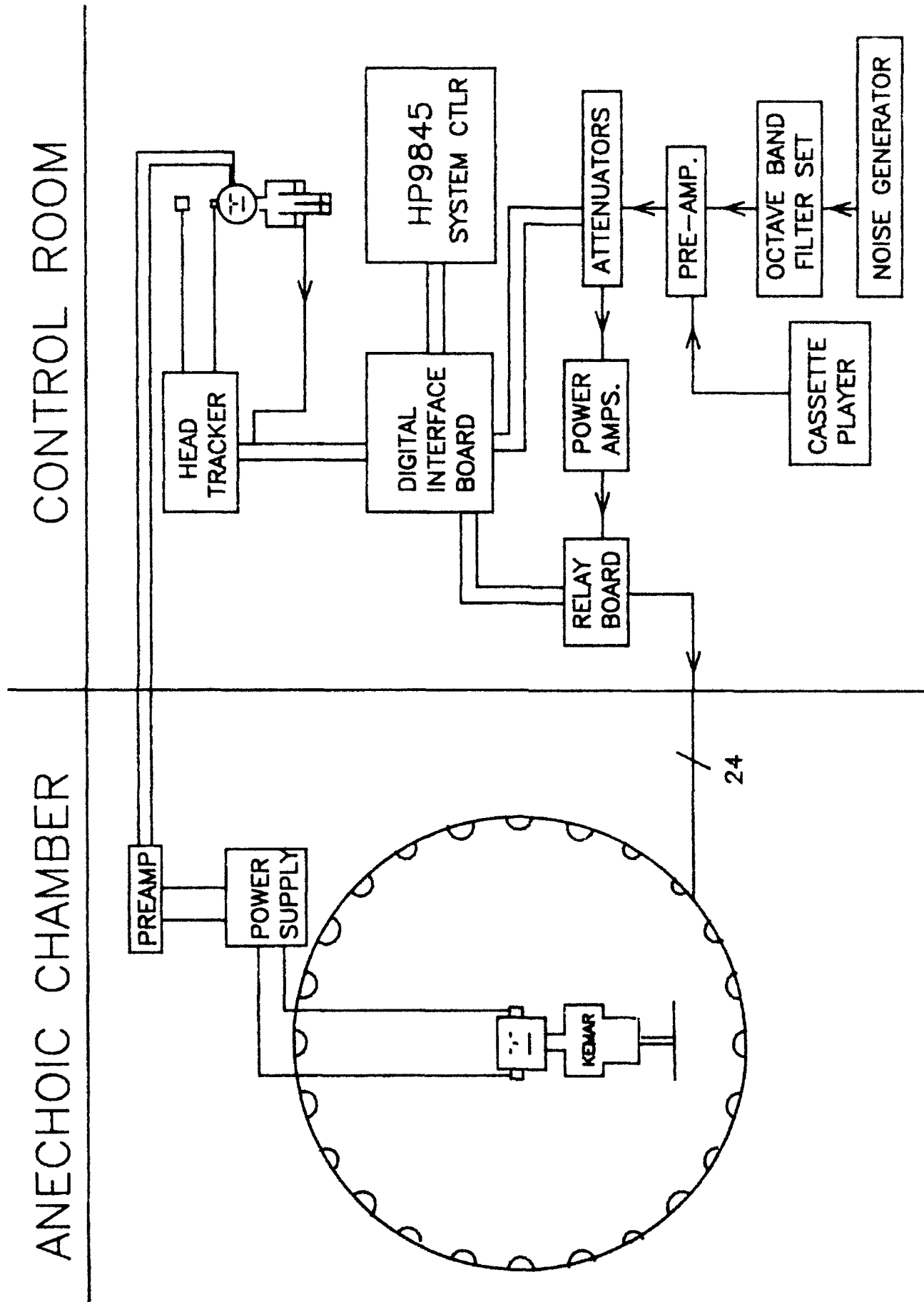
SETUP FOR SIMULATOR HUMAN PERFORMANCE MEASUREMENTS

FIGURE 2

SECTOR 1
330–29

SECTOR 2
30–89

SECTOR 3
90–149

SECTOR 4
150–209

SECTOR 5
210–269
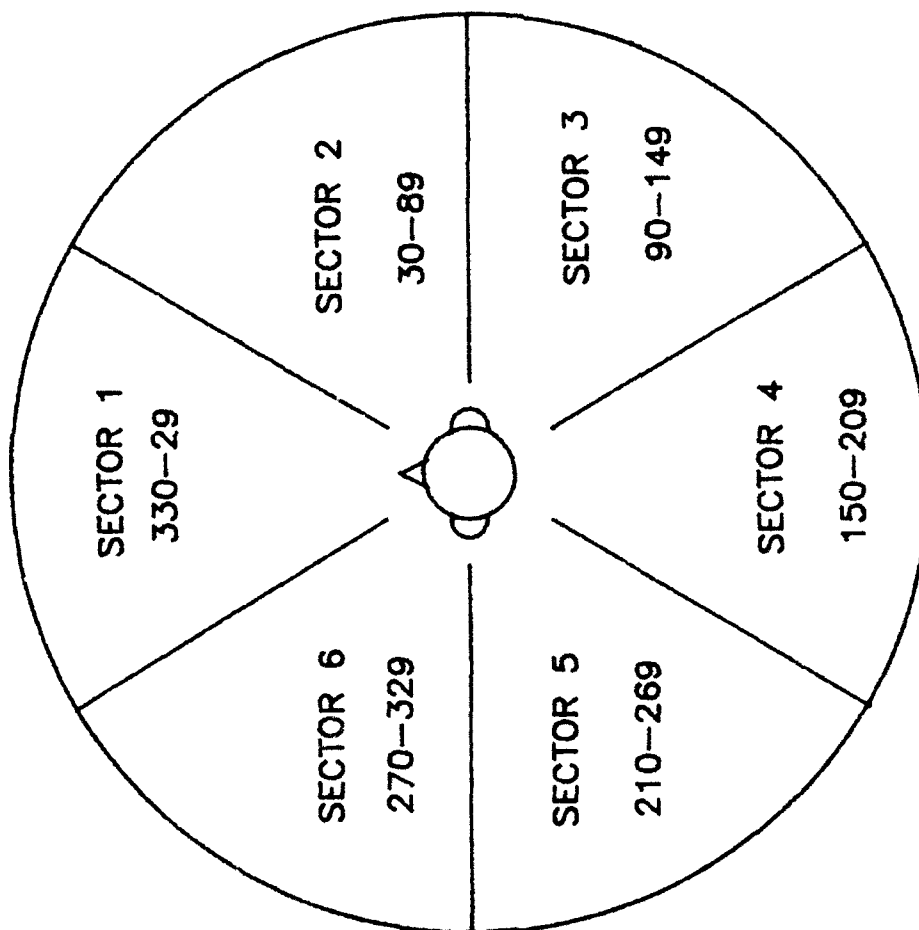
SECTOR 6
270–329

SECTORS OF STIMULUS PRESENTATION

FIGURE 3

18
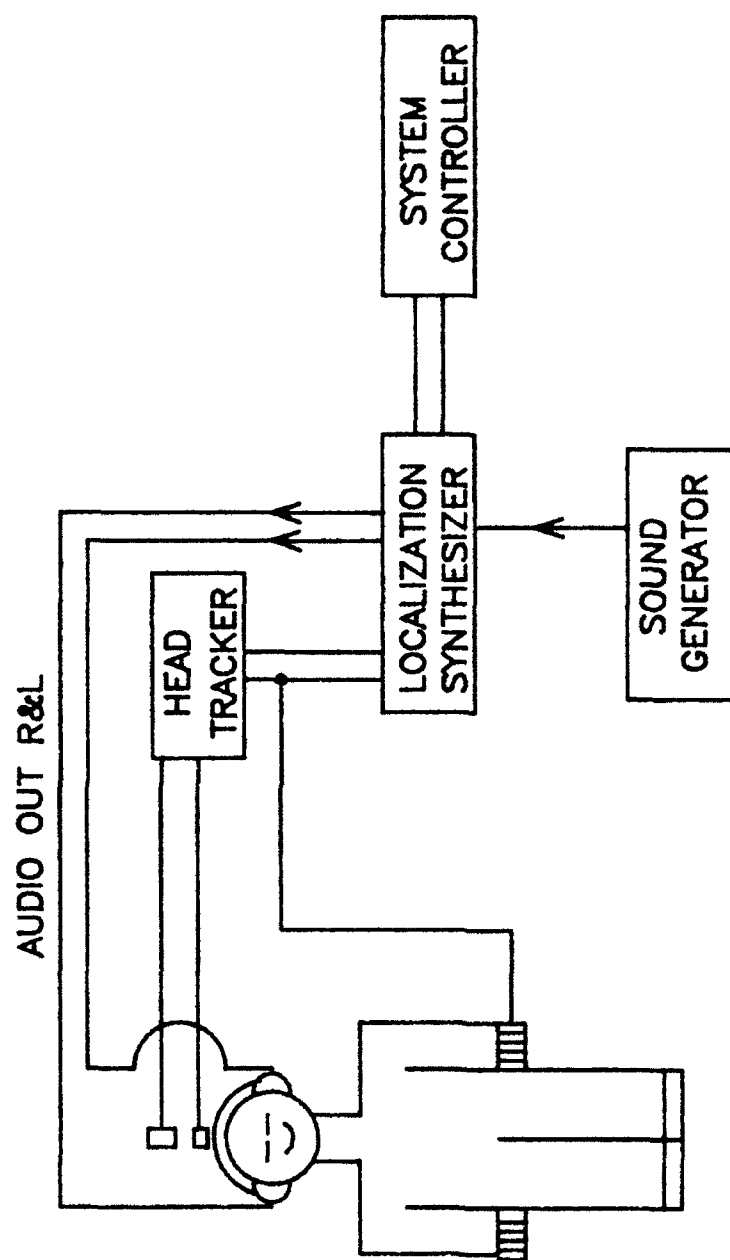
SETUP FOR SYNTHESIZER HUMAN PERFORMANCE MEASUREMENTS

FIGURE 4

MEAN MAGNITUDE ERROR BY CONDITION & SECTOR

FREE-FIELD ———

SIMULATOR – –
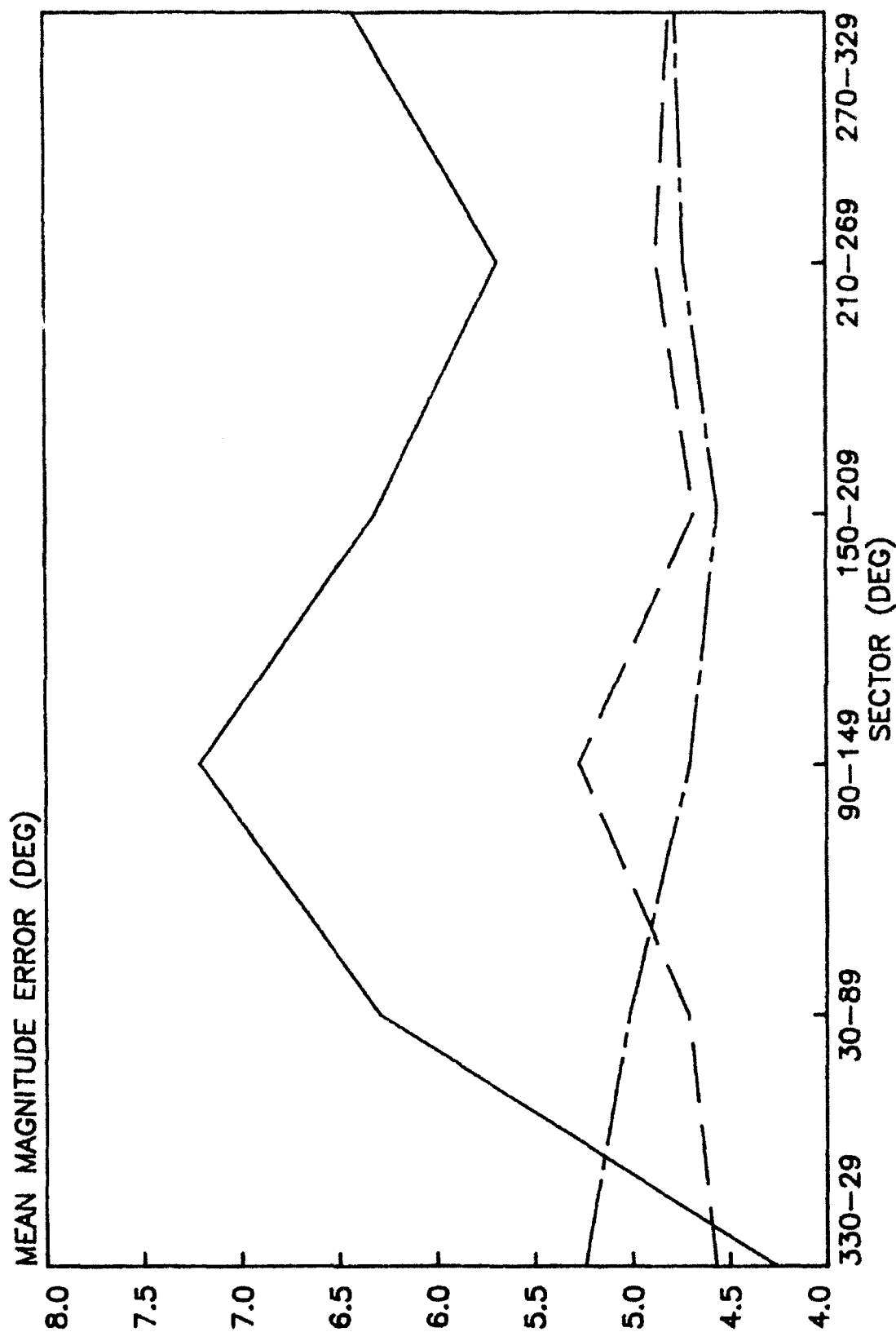
SYNTHESIZER – · –

FIGURE 5

MEAN DIRECTIONAL ERROR BY CONDITION & STIMULI

FREE-FIELD   SIMULATOR   SYNTHESIZER
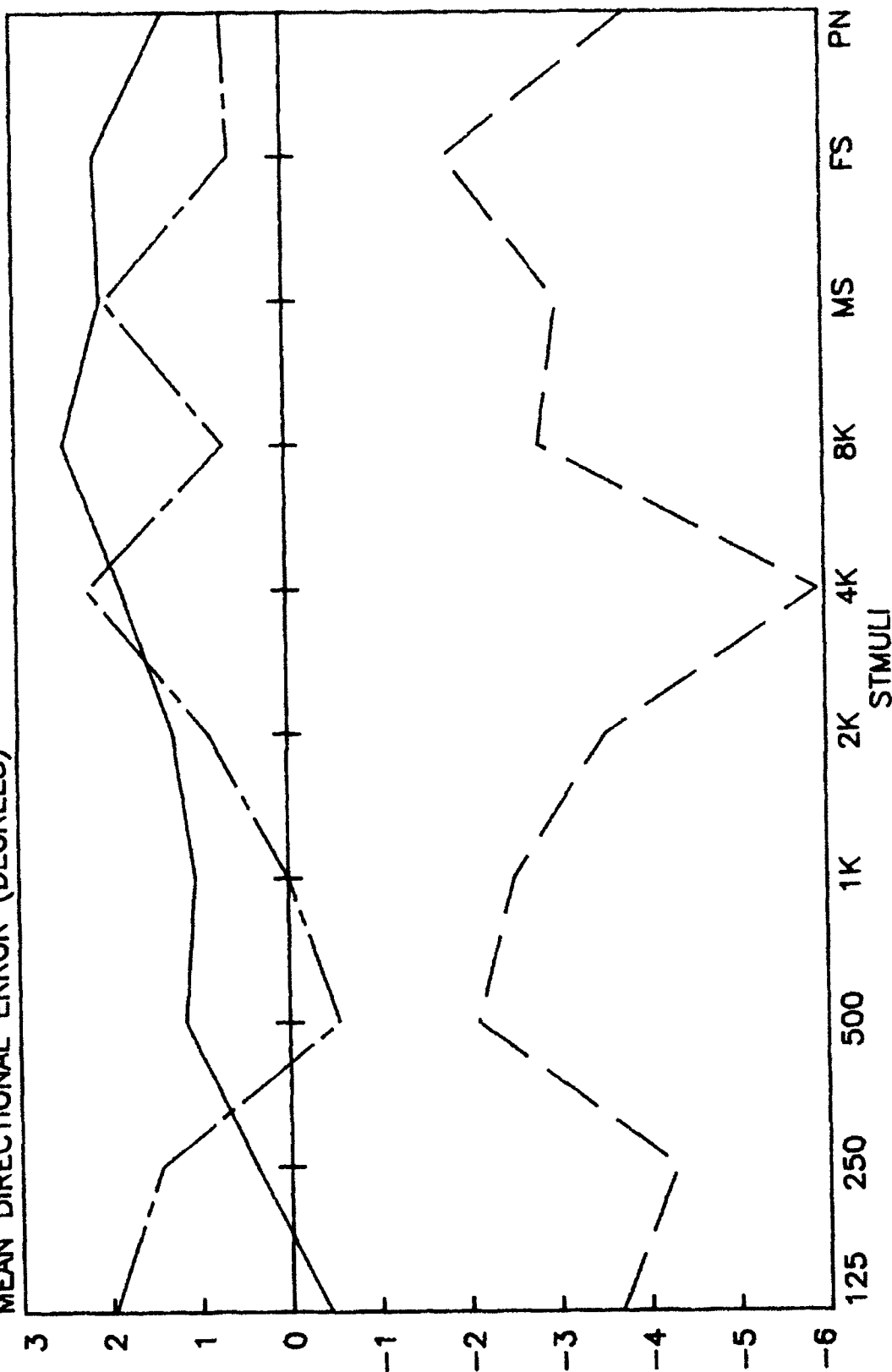
FIGURE 6

MEAN RESPONSE TIME BY CONDITION & STIMULI

FREE-FIELD   SIMULATOR   SYNTHESIZER

MEAN RESPONSE TIME (SECONDS)

STIMULI
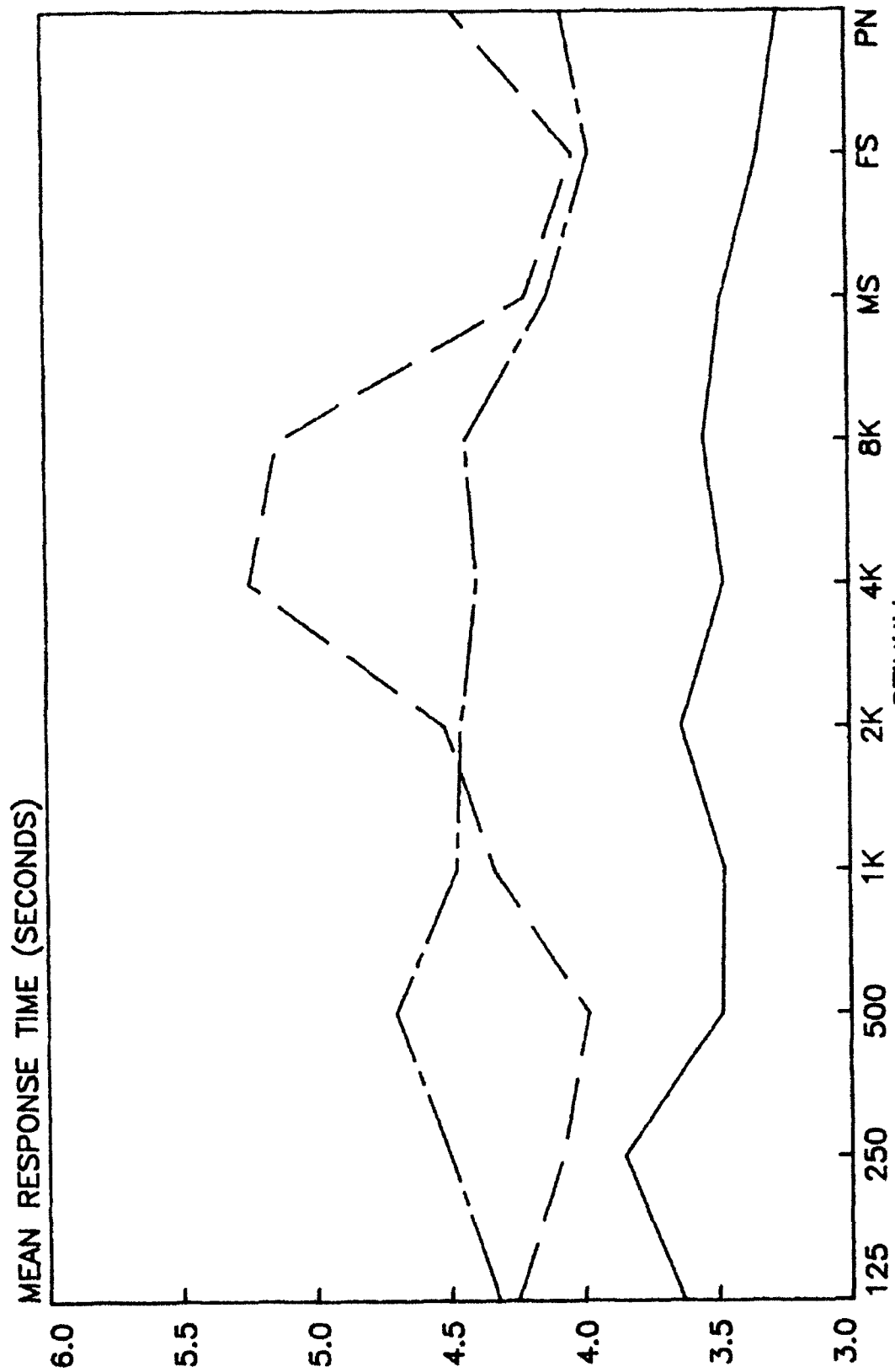
FIGURE 7

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Table 6
Mean Magnitude Error as a Function of Condition, Stimulus and Sector

	STIM	SECTOR 330-29	30-89	90-149	150-209	210-269	270-329
	125	4.65	6.27	7.45	7.55	7.14	6.18
	250	3.69	5.51	6.85	5.87	4.91	5.68
	500	3.82	6.10	6.81	6.13	4.95	6.18
	1K	3.88	6.63	8.07	5.91	4.77	5.68
FF	2K	4.87	7.52	8.92	6.82	5.61	6.15
	4K	5.13	5.73	7.48	6.71	5.44	6.66
	8K	4.11	6.93	7.68	6.52	5.85	7.03
	MS	4.10	6.16	6.21	5.57	5.66	6.91
	FS	4.40	5.46	6.37	6.04	6.62	6.88
	PN	4.00	6.59	6.21	6.03	5.84	6.85
	125	4.71	4.80	4.77	4.54	5.15	5.19
	250	4.94	5.17	5.52	4.97	5.09	5.71
	500	3.52	4.10	4.51	3.47	3.38	3.56
	1K	4.23	3.88	3.56	4.23	3.88	5.40
SIM	2K	4.43	4.35	5.91	4.68	5.08	4.75
	4K	6.70	6.89	7.13	6.82	7.43	6.68
	8K	4.95	4.99	5.55	5.17	5.43	5.25
	MS	4.05	4.14	5.37	4.28	4.45	4.37
	FS	3.77	4.45	3.93	3.94	3.75	4.02
	PN	4.36	4.29	4.62	4.96	5.01	4.81
	125	5.49	5.12	4.51	4.32	5.03	4.69
	250	6.07	5.15	4.94	4.52	5.31	5.86
	500	5.23	4.74	4.37	4.25	4.91	4.90
	1K	4.71	4.88	4.45	5.04	4.99	3.88
SYN	2K	5.33	4.82	4.35	4.23	4.20	4.90
	4K	5.58	6.21	5.68	6.25	5.38	6.09
	8K	4.46	4.89	4.23	3.87	4.64	4.40
	MS	5.36	4.60	5.01	4.70	4.42	4.07
	FS	5.35	4.83	4.72	4.09	4.02	3.62
	PN	4.86	4.89	4.72	4.36	4.42	5.32

Table 7
Mean Directional Error as a Function of Condition, Stimulus and Sector

| | | | | SECTOR | | | |
	STIM	330-29	30-89	90-149	150-209	210-269	270-329
	125	0.79	-1.11	-1.79	-1.69	-0.39	1.60
	250	0.70	0.26	-1.47	-0.61	0.97	2.43
	500	1.10	0.90	0.57	1.22	0.99	2.12
	1K	1.44	0.33	-1.02	1.04	1.07	3.32
FF	2K	0.41	1.79	0.16	0.67	0.55	4.01
	4K	1.15	1.72	-0.83	2.60	1.80	4.51
	8K	1.71	1.36	0.77	2.05	3.54	5.35
	MS	1.29	0.92	0.16	2.36	2.99	4.44
	FS	1.52	0.67	1.11	2.33	2.60	4.30
	PN	0.65	-0.55	-0.32	2.00	2.58	3.40
	125	-3.64	-3.24	-4.59	-4.27	-4.21	-4.59
	250	-4.27	-4.21	-4.58	-4.03	-4.19	-4.56
	500	-1.88	-2.40	-3.43	-2.13	-1.27	-1.58
	1K	-1.94	-2.46	-4.21	-2.35	-1.62	-2.54
SIM	2K	-3.14	-2.33	-4.72	-3.28	-4.19	-3.63
	4K	-5.77	-5.56	-6.39	-6.04	-6.36	-5.38
	8K	-2.16	-2.25	-4.21	-2.68	-2.99	-2.70
	MS	-2.40	-1.94	-4.21	-2.91	-3.27	-3.57
	FS	-1.25	-1.74	-2.04	-1.58	-1.62	-2.65
	PN	-3.85	-2.95	-3.71	-4.08	-4.41	-4.06
	125	1.03	3.27	2.99	1.73	0.89	1.92
	250	0.88	2.53	2.34	1.71	-0.60	1.70
	500	0.47	-1.44	-0.81	-0.22	-1.34	-0.04
	1K	-0.11	1.00	0.79	-0.60	-0.76	-0.34
SYN	2K	0.14	1.39	0.86	1.18	0.04	1.67
	4K	1.85	2.94	3.13	3.67	0.37	1.30
	8K	0.48	1.10	0.69	1.24	0.83	-0.27
	MS	1.59	2.71	1.75	2.32	1.59	1.89
	FS	0.29	0.58	0.20	0.29	1.14	1.06
	PN	0.64	2.23	1.03	0.92	-0.47	-0.37

Table 8
Mean Response Time as a Function of Condition, Stimulus and Sector

	STIM	SECTOR					
		330-29	30-89	90-149	150-209	210-269	270-329
FF	125	2.77	3.38	3.88	4.43	3.94	3.36
	250	2.99	3.62	4.12	4.56	4.19	3.61
	500	2.56	3.23	3.69	4.24	3.66	3.49
	1K	2.74	3.29	3.78	4.15	3.69	3.17
	2K	2.98	3.30	3.86	4.44	3.89	3.32
	4K	2.75	3.25	3.87	4.14	3.64	3.19
	8K	2.73	3.25	3.91	4.12	3.86	3.38
	MS	2.72	3.19	3.72	4.17	3.78	3.23
	FS	2.59	3.17	3.53	3.95	3.52	3.19
	PN	2.35	2.95	3.53	3.74	3.39	3.57
SIM	125	3.67	3.87	4.53	5.01	4.43	3.98
	250	3.33	3.75	4.17	4.87	4.42	3.93
	500	3.28	3.79	4.15	4.79	3.97	3.89
	1K	3.82	4.03	4.44	5.11	4.71	3.90
	2K	3.92	4.25	4.62	5.29	4.67	4.30
	4K	4.46	4.84	5.62	6.12	5.61	4.77
	8K	4.55	4.74	5.36	5.93	5.43	4.78
	MS	3.68	3.90	4.24	4.85	4.58	3.94
	FS	3.36	3.78	4.08	4.73	4.28	3.89
	PN	3.69	4.17	4.63	5.25	4.71	4.34
SYN	125	3.59	4.02	4.60	5.06	4.67	4.01
	250	3.76	4.38	4.69	5.25	4.76	4.14
	500	4.09	4.76	4.67	5.31	5.17	4.22
	1K	3.76	4.08	4.93	5.07	4.80	4.20
	2K	3.72	4.19	4.76	5.14	4.68	4.20
	4K	3.76	4.23	4.54	5.08	4.60	4.14
	8K	4.11	4.70	5.09	4.66	4.21	3.74
	MS	3.74	3.70	4.25	4.83	4.33	3.84
	FS	3.43	3.63	4.30	4.64	4.15	3.59
	PN	3.54	3.74	4.32	4.55	4.37	3.81